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AN OPTIMIZATION-BASED DECISION SUPPORT MODEL FOR THE NAVY H-60 HELICOPTER PREVENTIVE MAINTENANCE PROGRAM

by

Michael H. Albright

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Thesis Advisor:	Gerald G. Brown
Second Reader:	Ronald L. Brown


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For Naval aircraft, the largest portion of Operating and Support (O&S) costs is consumed by maintenance. The effort to reduce O&S costs is part of a Naval Air Systems Command initiative termed Affordable Readiness. Innovative programs are being implemented under Affordable Readiness to maintain safety, sustain readiness, and reduce costs.

One program, Integrated Maintenance Concept (IMC), is being developed for the Navy H-60 helicopter. IMC calls for depot-level artisans to be collocated at each squadron facility rather than at a central facility. Integrating appropriate organizational level maintenance tasks with germane subsets of the depot level tasks is the essence of the H-60 IMC. Reduced aircraft maintenance costs and out-of-service time are the major benefits of IMC.

As part of the transition to IMC, current organizational, intermediate and depot maintenance requirements are being reviewed for applicability and effectiveness. The result of this review will be a new listing of justified preventive maintenance tasks. The tasks will then be grouped into admissible maintenance evolutions that attempt to minimize total aircraft out-of-service time.

This thesis explores the potential synergism inherent to certain preventive maintenance task groupings that can lead to an overall reduction in aircraft out-of-service time. A prototypic optimization-based decision support model is developed. The solution presented is in terms of total cost in hours to perform all required tasks over a given time horizon. Additionally, the optimal task groupings are identified. Together, these results are insightful for developing a preventive maintenance program.

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AN OPTIMIZATION-BASED DECISION SUPPORT MODEL FOR THE NAVY H-60 HELICOPTER PREVENTIVE MAINTENANCE PROGRAM

Michael H. Albright
Commander, United States Navy
B.S., Florida State University, 1980

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ABSTRACT

For Naval aircraft, the largest portion of Operating and Support (O&S) costs is consumed by maintenance. The effort to reduce O&S costs is part of a Naval Air Systems Command initiative termed Affordable Readiness. Innovative programs are being implemented under Affordable Readiness to maintain safety, sustain readiness, and reduce costs.

One program, Integrated Maintenance Concept (IMC), is being developed for the Navy H-60 helicopter. IMC calls for depot-level artisans to be collocated at each squadron facility rather than at a central facility. Integrating appropriate organizational level maintenance tasks with germane subsets of the depot level tasks is the essence of the H-60 IMC. Reduced aircraft maintenance costs and out-of-service time are the major benefits of IMC.

As part of the transition to IMC, current organizational, intermediate and depot maintenance requirements are being reviewed for applicability and effectiveness. The result of this review will be a new listing of justified preventive maintenance tasks. The tasks will then be grouped into admissible maintenance evolutions that attempt to minimize total aircraft out-of-service time.

This thesis explores the potential synergism inherent to certain preventive maintenance task groupings that can lead to an overall reduction in aircraft out-of-service time. A prototypic optimization-based decision support model is developed. The solution presented is evaluated in terms of total cost in hours to perform all required tasks over a given time horizon. Additionally, the optimal task groupings are identified. Together, these results are insightful for developing a preventive maintenance program.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

For Naval aircraft, the largest portion of Operating and Support (O&S) costs is consumed by maintenance. The effort to reduce O&S costs is part of a larger Naval Air Systems Command (NAVAIR) initiative termed Affordable Readiness. The Affordable Readiness initiative has been developed because NAVAIR simply cannot afford to continue doing "business as usual." Consequently, innovative programs are being implemented under the Affordable Readiness plan that maintain safety, sustain readiness, and reduce O&S costs.

One of these programs, termed Integrated Maintenance Concept (IMC), is being developed for the Navy H-60 helicopter. Generally, IMC calls for depot-level artisans to be permanently located on-site at each squadron facility rather than at a central facility at Corpus Christi, Texas. Required depot-level repairs will be performed on-site at specific intervals, thereby eliminating the need to take the aircraft out of service at some point for Standard Depot Level Maintenance rework at Corpus Christi.

Integrating appropriate organizational level maintenance tasks with germane subsets of the depot level tasks is the essence of the H-60 IMC. The opportunity to reduce aircraft maintenance costs and out-of-service time are the major benefits of IMC. The result of a fully-implemented program will be increased readiness and reduced maintenance costs.

As part of the transition to IMC, Sikorsky Aircraft Company engineers are using Reliability-centered Maintenance to review all H-60 organizational, intermediate and depot maintenance requirements. Reliability-centered Maintenance is a process, which when overlaid on the normal in-service support system, works to achieve the inherent

reliability of components at the lowest possible cost through the optimization of scheduled maintenance.

H-60 Fleet Support Team engineers will compare the Sikorsky analysis with the existing preventive maintenance program, and reconcile any differences. The output of this review will be a new listing of H-60 preventive maintenance tasks. The problem then becomes how to group these tasks in an optimal manner that minimizes total aircraft out-of-service time.

This thesis explores the potential synergism inherent to certain preventive maintenance task groupings that can lead to an overall reduction in aircraft out-of-service time. For instance, it may take less time to perform a specific group of maintenance tasks in parallel, or as a combination of parallel and serial tasks, than to perform the same tasks serially.

A prototypic optimization-based decision support model is developed using representative maintenance tasks. The technique demonstrates proof of concept using preventive maintenance tasks from two major H-60 aircraft systems, the Rotor System and the Airframe System.

Because the results of reliability-centered maintenance analysis and review are not available at this writing, as they were expected to be, representative individual task performance times and task group times are used. However, the technique introduced here will accommodate actual task times and task group times when they finally become available.

The results presented are in terms of the minimum total cost in hours to perform all required tasks over a given time horizon. Additionally, the optimal task groupings are

identified. Together, these results are insightful for developing a preventive maintenance program.

In particular, it is clear that *fixed* time, the time required to remove an aircraft from service for maintenance, should probably be a key, explicit planning consideration when formulating task groupings. Otherwise, it is not clear how task packaging will have much beneficial effect on out-of-service time.

It is also important to note that each aircraft, because of its service experience and material condition, can be expected to present a unique opportunity for task packaging. The technique introduced here can be used to customize a task package for each aircraft, at every return to service, following every maintenance action. Such *continuously adaptive* maintenance planning can lead to an even greater reduction in out-of-service time and maintenance costs compared with the traditional "one-size-fits-all" preventive maintenance program.

The size and complexity of admissible task packages may be influenced by proximity of deployments or major airframe anniversaries. In these cases, it is expected that routine rules for scheduling maintenance groups might be adjusted to render "full up" aircraft at particular deadlines. The techniques introduced here can easily accommodate such real-world considerations.

The transition to a phased depot maintenance program like IMC represents a significant change in the aviation maintenance paradigm. This thesis encourages maintenance program developers to advance even further by implementing a progressive, continuously adaptive and customized preventive maintenance program that realizes the absolute lowest cost and highest readiness.

ACKNOWLEDGEMENTS

I would like to thank Mr. Bruce Pollock of the Navy H-60 Fleet Support Team for his continual support of this effort. His assistance in providing information and access to key points of contact in the H-60 community were instrumental in ensuring the success of this thesis.

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I. INTRODUCTION

A. BACKGROUND

For Naval aircraft, the largest portion of Operating and Support (O&S) costs is consumed by maintenance (CNASC, 1996a). The effort to reduce O&S costs is part of a larger Naval Air Systems Command (NAVAIR) initiative termed Affordable Readiness. The Affordable Readiness initiative has been developed because naval aviation simply cannot afford to continue doing "business as usual." (CNASC, 1996b) Consequently, innovative methods are being implemented under Affordable Readiness to maintain safety, sustain readiness, and reduce O&S costs. Figure 1 shows H-60 Operating and Support cost percentages for various categories.

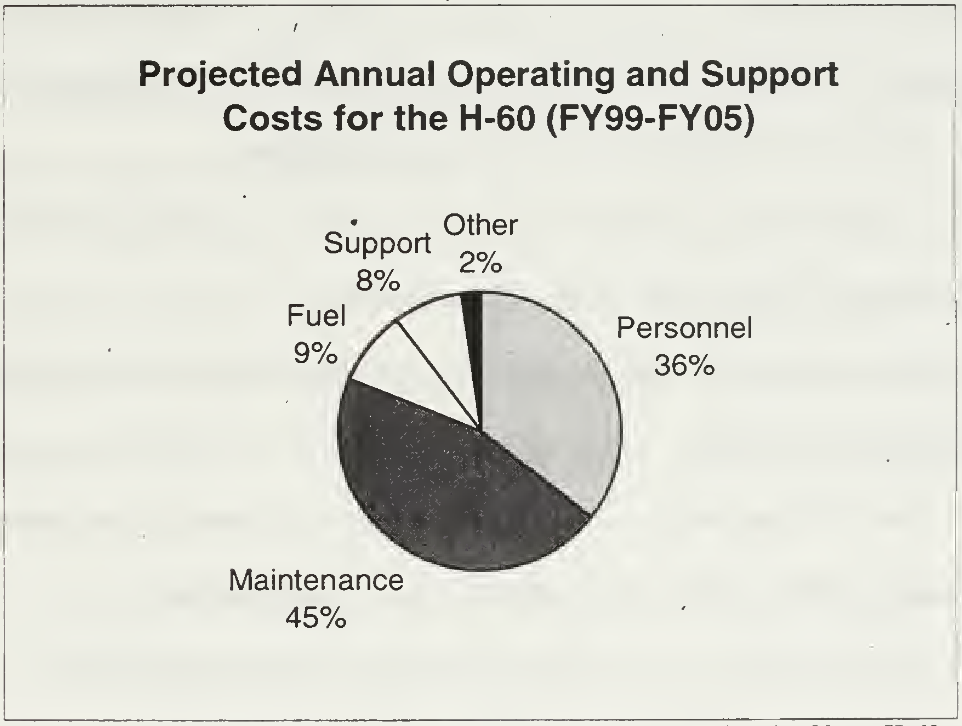


Figure 1. Projected Annual Operating and Support Costs for the Navy H-60. The Navy spent more than 4.5 billion dollars on aviation maintenance in FY96 (Thomas, 1997). Maintenance costs account for the largest portion of overall Operating and Support costs. The H-60 Operating and Support cost breakdown is consistent with all of Naval Aviation. (Pollock, 1997b)

A key element of Affordable Readiness is Sustained Maintenance Planning. This concept enables program managers to sustain readiness of in-service weapons systems by using key performance indicators to trigger maintenance, modification, or even redesign. NAVAIR's Affordable Readiness plan considers Reliability-centered maintenance (RCM) as one of its primary money-saving tools under Sustained Maintenance Planning. RCM is a process, which when overlaid on the normal in-service support system, works to achieve the inherent reliability of components at the lowest possible cost through the optimization of scheduled maintenance (CNASC, 1996a).

B. TRADITIONAL MAINTENANCE PROGRAM

A maintenance program includes both scheduled and unscheduled maintenance. Scheduled maintenance is performed for the purpose of avoiding failures, whereas unscheduled maintenance is performed to repair failures that have already occurred.

An effective maintenance program has four objectives:

- maximize the probability that assets are capable of providing required functions while achieving inherent levels of reliability and safety;

- restore required functional capability and inherent levels of reliability and safety when deterioration occurs;

- obtain the information necessary for design improvement for those items whose functional capabilities and inherent reliability prove inadequate; and

- accomplish these objectives at the least cost possible. (ATAA, 1993)

Scheduled maintenance is defined as *"a justified task (one which is both applicable and effective) that is accomplished at a scheduled interval to maximize the*

probability that an item is capable of providing the required function while achieving the level of safety and reliability inherent to its design." (CNASC, 1997) A collection of such tasks, together with their assigned intervals, is the foundation of the Preventive Maintenance program.

A preventive maintenance program that is based on the RCM philosophy must be dynamic – it must respond to changes resulting from actual field experience. As weapons systems age, maintenance organizations must be prepared to continually refine and modify the preventive maintenance program. (CNASC, 1996a)

C. RELIABILITY-CENTERED MAINTENANCE

RCM is defined as *"a disciplined logic or methodology used to maximize the probability that an asset is capable of providing its required function while achieving its inherent reliability through well-designed preventive maintenance tasks at the least expenditure of resources."* (CNASC, 1997)

RCM has been used to some extent since the 1960s, but with the advent of the Affordable Readiness initiative, RCM has been brought to the forefront as a primary tool for determining justified preventive maintenance tasks. The three primary objectives of RCM are:

- maintain functional capability at or above the level required by the user;

- retain the inherent reliability designed into the system through justified preventive maintenance tasks designed to prevent age-related functional failures; and

- achieve the desired results with the least expenditure of resources by logically selecting only those preventive maintenance tasks that effectively manage failures which degrade safety, reduce mission capability, or cause extensive damage. (CNASC, 1997)

Application of RCM yields justified preventive maintenance tasks that are subsequently implemented at the appropriate maintenance level (organizational, intermediate, or depot) of the Naval Aviation Maintenance Program. Five types of preventive maintenance tasks can be performed, each of which is applicable under a unique set of conditions. The preventive maintenance task types are:

- **servicing tasks** that replenish consumable materials that are depleted during normal operations;

- **lubrication tasks** that are scheduled maintenance functions designed to replace a lubricant based on the manufacturer's predicted or measured life of the lubricant;

- **on-condition tasks** that are scheduled inspections of an item to look for a specific indication of potential failure (these do not include the corrective action taken to regain the item's functionality);

- **hard time removal tasks** that remove an item at or before some specified age limit; and

- **failure finding tasks** that are performed at specified intervals to expose the occurrence of a functional failure that is not evident to the crew while performing its normal duties (these do not include the corrective action taken to restore the item's functionality). (CNASC, 1997)

In addition to justified preventive maintenance tasks, RCM analysis may produce two other outcomes:

- **no preventive maintenance required**; or

- **redesign required**.

D. FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

The Failure Mode, Effects and Criticality Analysis (FMECA) *"identifies and documents the functions, functional failures and engineering failure modes of a system's significant items."* (CNASC, 1997) The FMECA also identifies how failures might affect the local item (significant item), e.g., a main rotor blade, the next higher assembly (system or subsystem), e.g., the main rotor system, and the end item, e.g., the aircraft. The FMECA further classifies the severity of each failure effect according to established severity classification criteria.

A FMECA is made up of two steps:

Step 1 - The **Failure Mode and Effects Analysis** *"ascertains the function of each item, determines the functional failure associated with each function, identifies the engineering failure mode that creates the functional failure, and determines the effect that each engineering failure mode (EFM) has on the system."* (CNASC, 1997)

Step 2 - The **Criticality Analysis** is used to rank each failure mode identified in the Failure Mode and Effects Analysis *"according to the combined influence of the severity classification and its probability of occurrence."* (CNASC, 1997) Criticality analysis prioritizes investigations to identify changes that will reduce potential impact on maintenance and logistic support requirements.

E. SIGNIFICANT ITEM SELECTION

"Significant" item selection is necessary because applying RCM analysis to every component in a weapon system is neither cost effective nor necessary to ensure reliability. The information used to develop the significant item candidate list ordinarily comes from the FMECA. Careful selection of only those items that are truly significant will improve not only the effectiveness of the RCM analysis, but also the effectiveness of the resulting preventive maintenance program. RCM provides a means for separating potential significant items into three general categories:

- **structurally significant items** (SSI) whose failure will result in a direct adverse effect on operating safety;

- **functionally significant items** (FSI) whose loss of function will have significant safety, operational, or economic consequences at the equipment level; and

- **nonsignificant items** whose loss of function will nave no significant safety, operational or economic consequences at the equipment level. (CNASC, 1997)

When the "structural" logic determines that a preventive maintenance task is applicable and effective, one of two task types is justified; an **on-condition** task or a **hard time** task. When the outcome of the "functional" logic determines a preventive maintenance task is applicable and effective, one of the five task types is justified.

Once a particular preventive maintenance task type is selected, the task must be defined and its interval determined. The inspection intervals are determined in accordance with the "rules" established for the preventive maintenance task type (e.g., DoD, 1985).

F. INTEGRATED RELIABILITY-CENTERED MAINTENANCE SYSTEM

The Integrated Reliability-Centered Maintenance System (IRCMS) is the primary tool used by RCM analysts to develop justified preventive maintenance tasks. IRCMS provides a means of automating RCM to *"determine the applicability, effectiveness and preliminary inspection intervals of potential PM tasks."* (CNASC, 1997) Once the data is entered, preventive maintenance tasks are evaluated until one is proven to be applicable and effective, at which time that task is recommended. Or, if none of the preventive maintenance tasks meets the established applicability and effectiveness criteria, then either no preventive maintenance task is needed or redesign of the item is in order. Figure 2 shows the relationship between the Integrated Reliability-centered Maintenance System and RCM.

RCM identifies a set of preventive maintenance tasks that achieves required levels of reliability, safety and readiness for a system. Once identified, these tasks must be *packaged* into a preventive maintenance program. The underlying philosophy of the preventive maintenance program determines how the tasks are incorporated into the program. Gertsbakh (1977) and Kececioglu (1995) present examples of a wide variety of preventive maintenance programs, and are excellent background references for preventive maintenance program development.

The subsequent section describes two preventive maintenance programs for the H-60 helicopter. Once the type of preventive maintenance program is identified, the tasks can be packaged according to its requirements.

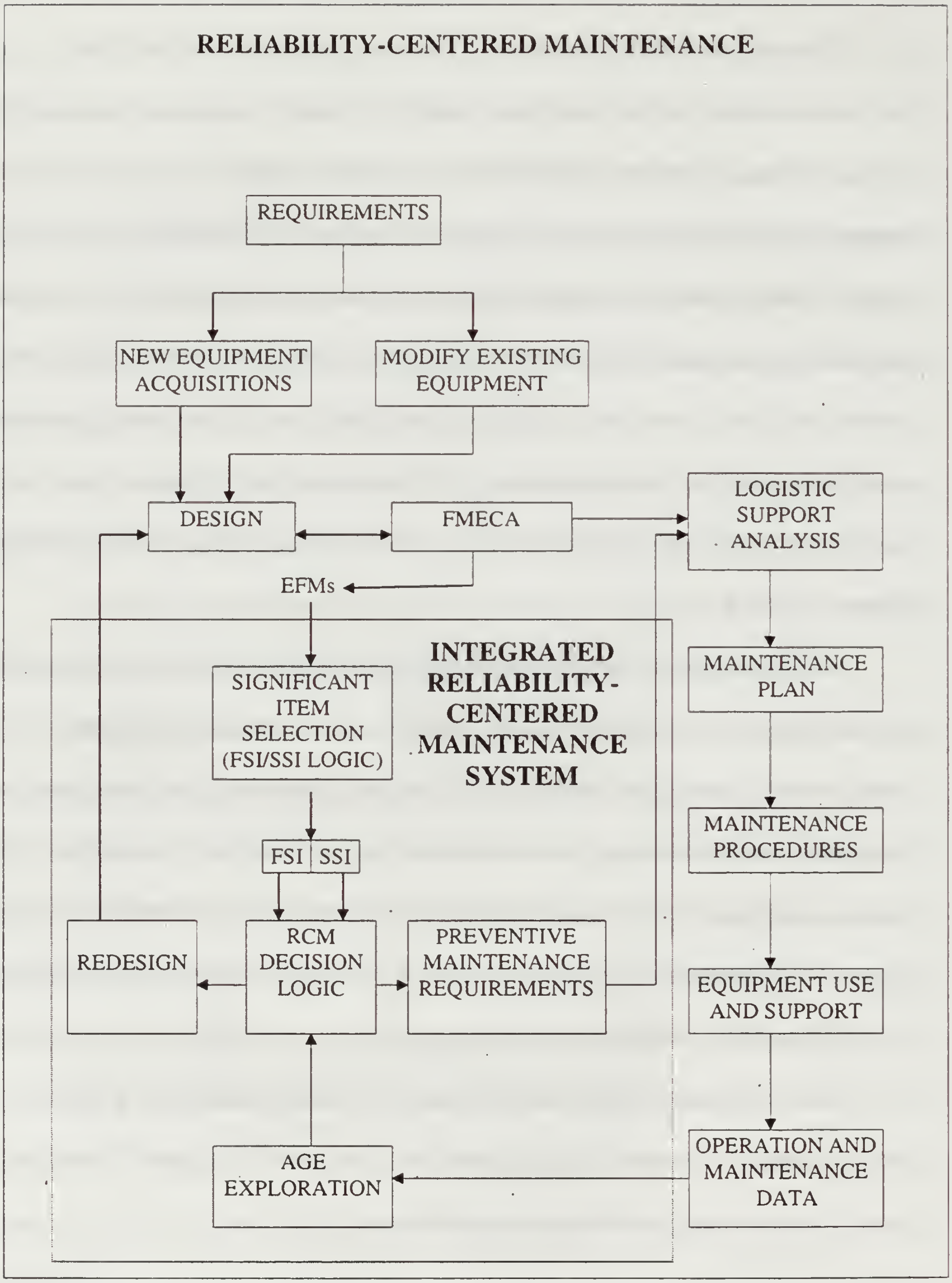


Figure 2. Reliability-Centered Maintenance. The Failure Mode, Effects and Criticality Analysis (FMECA) identifies the engineering failure modes. The Integrated Reliability-Centered Maintenance System selects justified, applicable and effective preventive maintenance tasks for each engineering failure mode (EFM). (CNASC, 1997)

II. NAVY H-60 HELICOPTER MAINTENANCE

A. NAVY H-60 HISTORY AND MISSION

The newest aircraft in the Navy's helicopter fleet today is the Sikorsky H-60 Seahawk, shown in Figure 3. Three main models of the SH-60 have been deployed: the SH-60B, SH-60F and HH-60H. The SH-60B was placed in service in 1983 as the replacement for the SH-2F, and its missions include aircraft carrier middle/outer zone anti-submarine warfare, anti-surface warfare, vertical replenishment, search and rescue and medical evacuation. The B model currently exists in three basic configurations: the original Block 0, the Block 1 upgrade, and the Middle Eastern Force configuration. The SH-60F was delivered to the Navy in 1989 as the replacement for the SH-3. The SH-60F deploys with the carrier and its missions include inner zone anti-submarine warfare, search and rescue and medical evacuation. The SH-60H, also delivered in 1989, deploys in support of combat search and rescue and Special Forces missions. (Patterson, 1997)

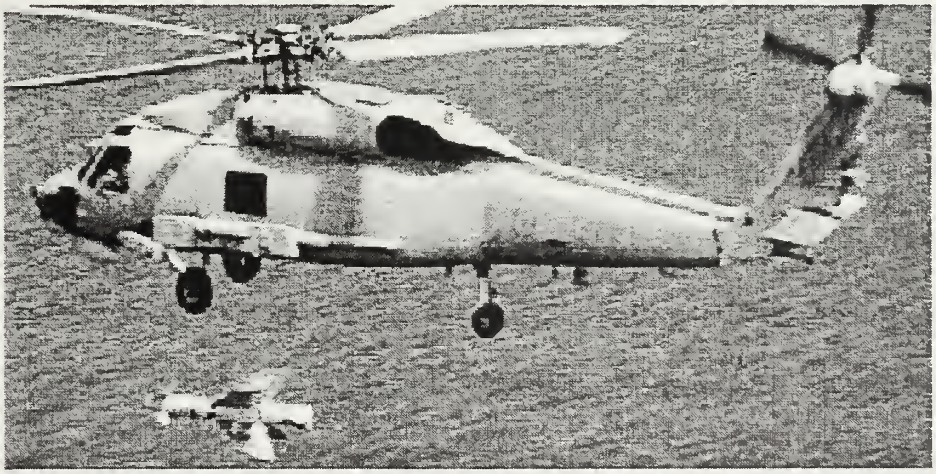


Figure 3. Navy SH-60 Helicopter. The H-60 is the Navy's newest helicopter. More than 2,500 separate periodic and recurring preventive maintenance actions are required to keep this aircraft flying.

B. THE "STATUS QUO" H-60 PREVENTIVE MAINTENANCE PROGRAM

The present Navy H-60 preventive maintenance program is a cycle consisting of periodic, recurring scheduled maintenance and inspection requirements at the squadron level, Aircraft Service Period Adjustment (ASPA) inspections and Special Depot Level Maintenance (SDLM) "visits."

Maintenance Requirements Card tasks are periodic scheduled maintenance and inspection requirements performed at the squadron level. The current Maintenance Requirement Card schedule calls for periodic inspections in the following categories:

- **turnaround inspections**;
- **daily inspections**;
- **calendar inspections** conducted at intervals of 7, 14, 28, 112, 224 and 365 days;
- **special inspections**;
- **conditional inspections**; and
- **phase A,B,C,D inspections** conducted at 150 flight hour intervals.

The turnaround, daily and calendar (7, 14 and 28 day) inspections are primarily "safety of flight", operating material condition, cleaning, servicing and lubrication requirements. General corrosion inspections are accomplished during the 28 day calendar inspection. The 56, 112, 224 and 365 day calendar inspections require detailed corrosion inspections over large areas of the aircraft, and take an extensive amount of time to complete. Because of the extended out-of-service time required to accomplish these inspections, maintenance personnel use these opportunities to perform any major corrosion treatment.

Special and conditional inspections address both cyclic requirements (e.g., every 100 landings) and conditional requirements (e.g., hard landing). Phase inspections address requirements that are based on flight hour accumulation; each phase is initiated upon the accumulation of 150 flight hours.

The ASPA program is an aircraft material condition sampling inspection based on the aircraft's Operational Service Period; 48 months for the SH-60B and 36 months for the SH-60F/H. Each aircraft receives an ASPA inspection near the end of its service period. If the aircraft "fails", it is inducted into Standard Depot Level Maintenance (SDLM). If the aircraft "passes" the inspection, its Period End Date is extended another year, whereupon another ASPA is conducted. The average ASPA extension for a "first tour" aircraft (an aircraft that has not yet had its first SDLM period) is 48 months (4 consecutive 1-year extensions). The average ASPA extension for a "second tour" aircraft (an aircraft that has been to SDLM once) is 24 months (2 extensions). (CNASC, 1991)

SDLM specifications direct structural inspections and repairs, systems repair and replacement, and stripping and painting. SDLM is an extensive overhaul effort which restores the overall aircraft condition to a standard that can be maintained at the squadron level. Currently, most Navy H-60 aircraft undergo SDLM at Corpus Christi Army Depot. **Turnaround time for H-60s delivered to Corpus Christi for SDLM averages more than 500 days at an average cost of more than 2 million dollars per aircraft** (Lyons, 1997). The long turnaround time at SDLM is exacerbating the already low aircraft availability rates of an aging helicopter fleet (Figure 4). Additionally the expense of sending an aircraft to SDLM is becoming increasingly insupportable under current Navy fiscal constraints (Figure 5).

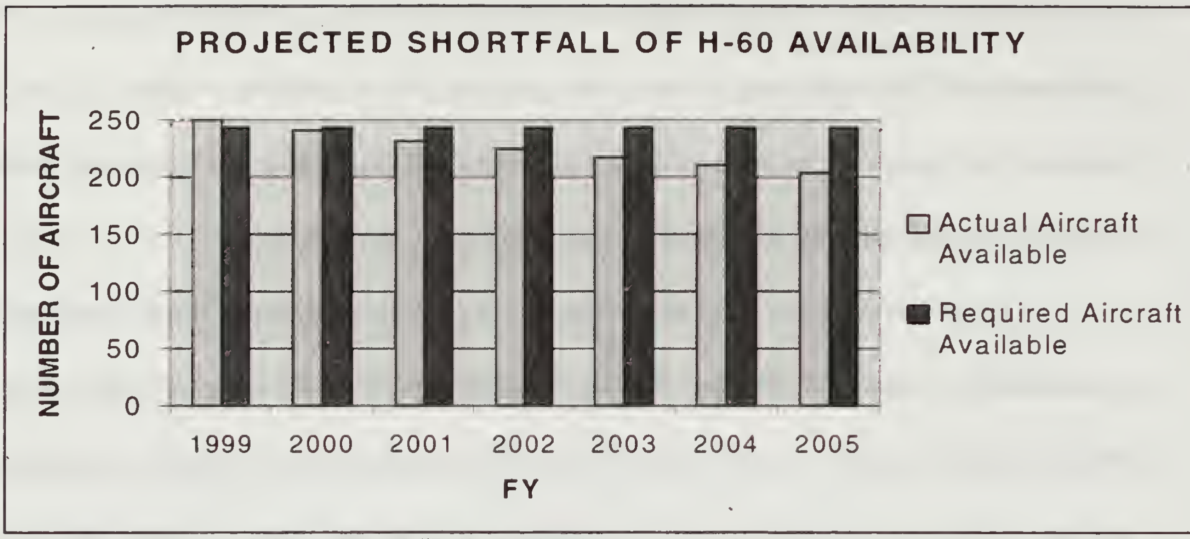
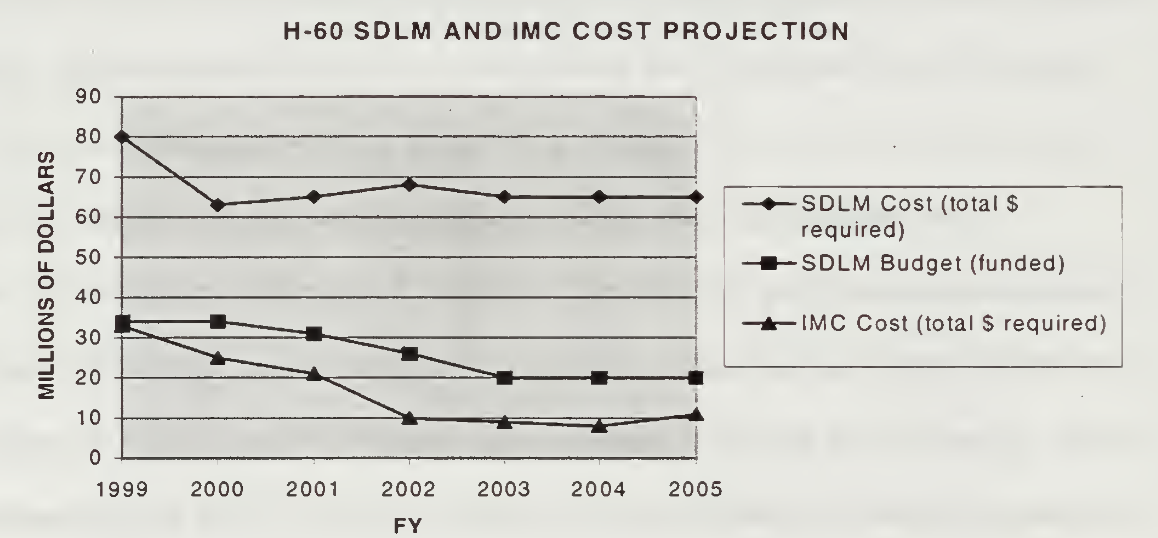


Figure 4. Projected Shortfall of H-60 Availability. Aircraft availability under the Aircraft Service Period Adjustment and Standard Depot Level Maintenance program decreases steadily over the years from 250 aircraft available in FY99 to a projected 204 aircraft available in FY05. Meanwhile the minimum number of H-60 aircraft required to support operational commitments remains at 243. (Pollock, 1997a)



FY	1999	2000	2001	2002	2003	2004	2005
Required SDLM slots	56	44	45	48	45	45	45
Funded SDLM slots	24	24	22	18	14	14	14
SDLM Shortfall Under Current Program	32	20	23	30	31	31	31
Shortfall Under SDLM and IMC	10	10	8	0	0	0	0

Figure 5. H-60 Standard Depot Level Maintenance and Integrated Maintenance Concept Cost Projection. The shortfall in SDLM slots is the difference between the number of slots required and the number of slots funded. IMC resolves the shortfall by FY 2002 at a cost substantially less than SDLM. (Pollock, 1997a)

C. THE "NEW" H-60 INTEGRATED MAINTENANCE CONCEPT

The combination of limited fleet inventory, increased operational commitments and DoN budgetary pressures (see Figure 5) on the SDLM program have mandated a change in maintenance practices for the H-60 (Beck, 1997). Accordingly, a phased depot maintenance plan, termed Integrated Maintenance Concept (IMC), is being developed that will combine all levels of maintenance on-site and in one package.

Generally IMC calls for depot-level artisans to be permanently collocated on-site at each squadron facility, performing required depot-level repairs at specific intervals as needed, thereby eliminating the need to take the aircraft out of service for a longer period at some point for remote SDLM rework. Integrating appropriate organizational level maintenance tasks with germane subsets of the SDLM tasks is the essence of the H-60 IMC.

IMC requires the packaging of scheduled maintenance tasks so that **all levels** of preventive maintenance can be performed **concurrently and as close to the flight line as feasible and economical**. IMC eliminates the preconceived notion that weapons systems must have all depot maintenance performed at a remote, centralized depot facility. IMC views depot maintenance as a capability, not a place. The opportunity to reduce out-of-service time is a major benefit of IMC.

As part of the transition to IMC, Sikorsky Aircraft Company engineers are using RCM to review organizational, intermediate and depot maintenance requirements. The resulting FMECA will be delivered to the H-60 Fleet Support Team. Fleet Support Team engineers will compare this FMECA with the existing preventive maintenance program,

and reconcile any differences. The output of this review will be a new listing of preventive maintenance tasks.

These preventive maintenance tasks must then be packaged in a manner that satisfies the H-60 IMC requirement for an integrated organizational, intermediate and depot preventive maintenance program.

III. TASK GROUPING AND TASK PACKAGING FOR H-60 INTEGRATED MAINTENANCE CONCEPT

A. FIXED AND VARIABLE TIME FOR TASK GROUPINGS

Aircraft out-of-service time, the time required to take an aircraft out of service for preventive maintenance, is influenced by the way the preventive maintenance tasks are grouped in a complete task packaging.

A task group has fixed and variable time components. **Fixed time** is the "overhead" time required to prepare the aircraft for maintenance (i.e., place the aircraft in a maintenance status). Fixed time is applied just once to each task grouping, regardless of the number or complexity of tasks included in the grouping. When an aircraft is in a maintenance status, it is not available for flight operations; therefore, fixed. time contributes to out-of-service time.

Task performance time is the time required to complete an individual maintenance task.

Variable time is the time required to complete all candidate tasks that make up the task grouping. Fixed and variable time influence the task group time. Three cases are possible for describing variable time (refer to Figure 6):

serial case – all tasks are performed "end-to-end". Variable time is the sum of the task performance times of each individual candidate task in the grouping;

parallel case – all tasks are performed concurrently. Variable time is the longest task performance time of the candidate tasks; and

synergistic case – a mixture of the above. Variable time in the synergistic case is the sum of the variable time for serial tasks, plus the longer variable time for parallel

tasks. The synergistic case may include complex partial orderings (e.g., tasks A and C may be performed in parallel, but both tasks must be completed prior to performing task B). Figure 7 illustrates examples of such partial orderings.

It is not reasonable to conclude that all tasks can be performed concurrently. Therefore, the focus of the task packaging problem is on the synergistic case since this is where the greatest efficiencies resulting from optimized task groupings are likely to be found.

The **task group time** is the sum of fixed time and variable time components for a task group. *This is the aircraft out-of-service time.*

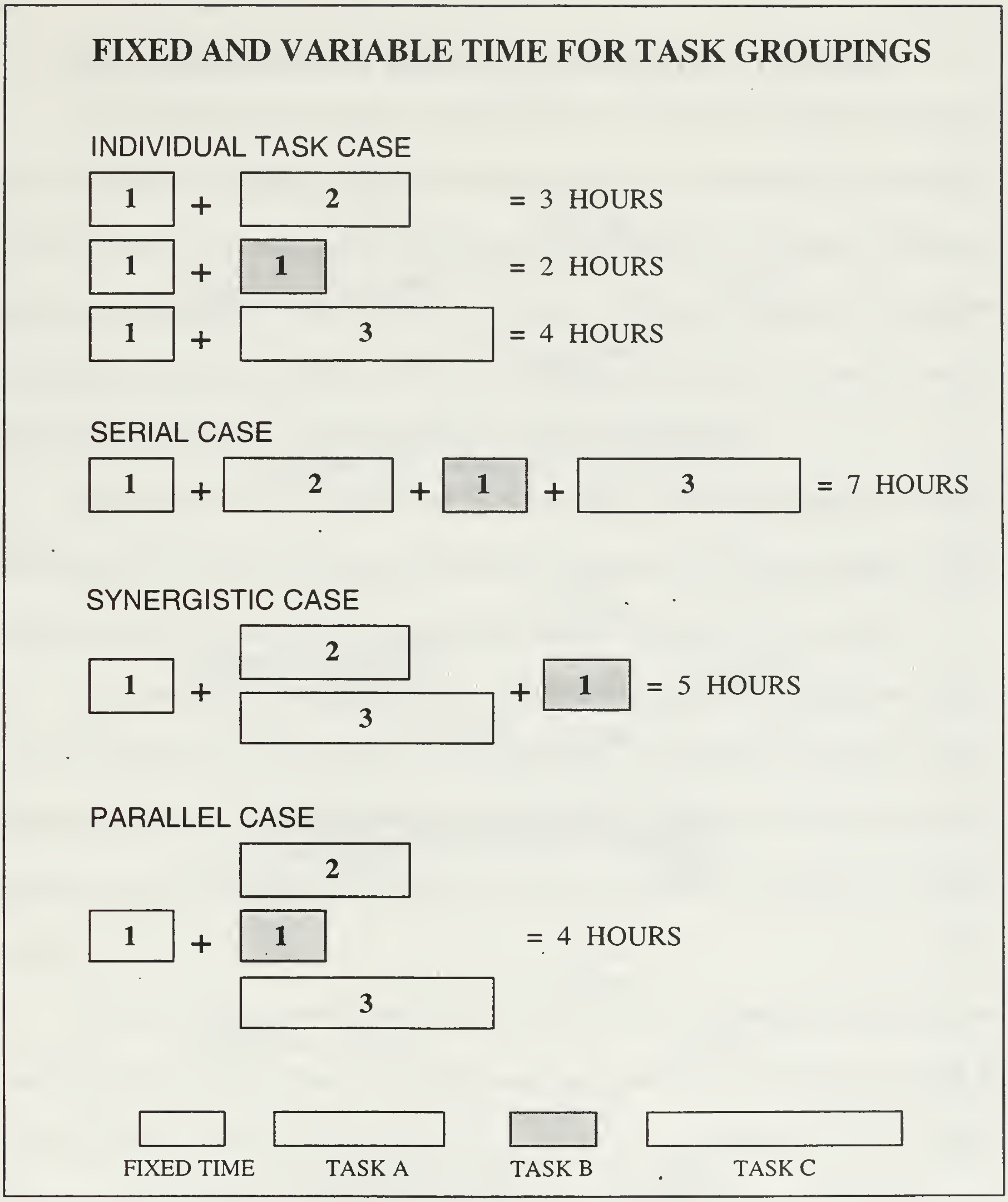


Figure 6. Fixed and Variable Time for Task Groupings. This three-task example illustrates how fixed and variable times affect task group time. The shaded boxes represent the tasks. The task performance time, in hours, is shown inside each task box. A fixed time of one hour, represented by a non-shaded box, is incurred just once for each task grouping. The individual task case shows that each task performed separately incurs a fixed time. In the serial case, tasks are completed end-to-end, therefore the task group time is seven hours. In this particular synergistic case, tasks A and C are performed concurrently, and when both are complete, task B is performed. The task group time is five hours. In the parallel case, tasks A, B and C are performed concurrently, and the task group time is four hours.

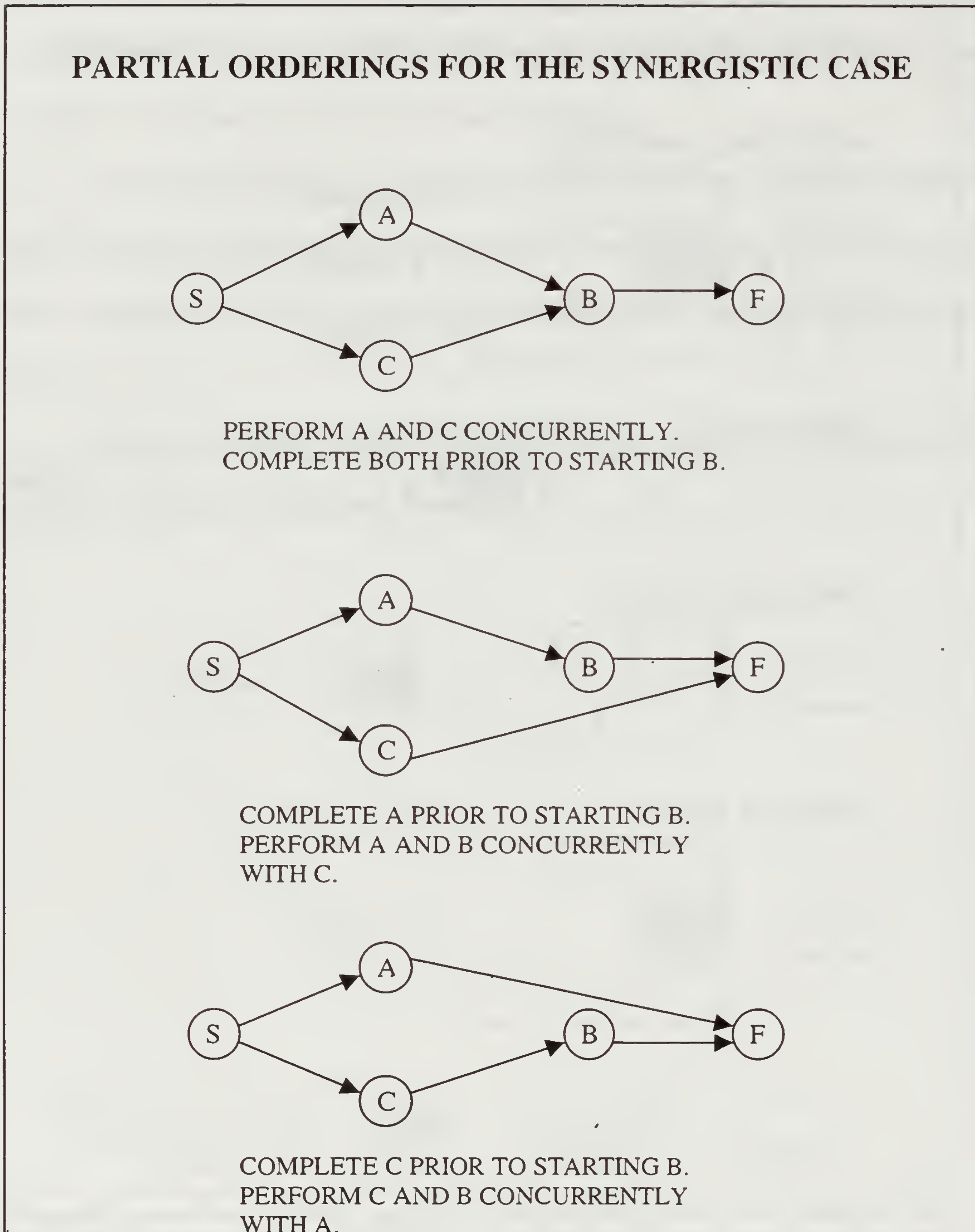


Figure 7. Partial Orderings for the Synergistic Case. This figure illustrates several partial orderings possible for a three-task example. Nodes A, B and C represent the three tasks. "S" and "F" represent the start and finish nodes for this task group. Each arrow depicts the partial order between the pair of tasks it connects. Note that, in each synergistic case, some tasks may be performed concurrently, while others must be performed serially. An interpretation is provided for each example. Complex partial orderings may exist for task groups having a large number of tasks.

B. CURRENT TASK PACKAGING

Task packaging incorporates a large number of maintenance tasks into groups of tasks that may be performed at approximately the same time. Currently task packaging is a labor-intensive manual manipulation of the preventive maintenance tasks into groupings that appear to make sense to experts. While this method has produced satisfactory results in the past, it is difficult to gauge total aircraft out-of-service time for the groupings selected.

Additionally, over time, preventive maintenance tasks may be added or deleted, and intervals of existing tasks may be extended or shortened. No methodology is in use that calculates the overall effect of these adjustments on total out-of-service time.

As a result, to bridge the gap from RCM to IMC, the H-60 IMC Team Leader identified the need to *"demonstrate and document an automated program that groups justified preventive maintenance tasks into optimal groupings with the objective of minimizing total aircraft out of service time, subject to various constraints."* (Pollock, 1997b)

There is no guidance for what optimal means, but this thesis assumes that task packaging must either influence the time out of service for the aircraft, or at least the number of times the aircraft is taken out of service. Accordingly, fixed and variable components are inferred for maintenance time. It is further conjectured that there may be some parallelism exploitable in performing tasks within a task group.

It is important to note that each aircraft, because of its service experience and material condition, can be expected to present a unique opportunity for task packaging.

For example, suppose that during a scheduled on-condition inspection, a component is discovered to have a defect that causes it to be removed and replaced. Because this corrective maintenance is performed during a scheduled interval, no change to the existing task package may be required. However, if this same component fails at some random time and has to be replaced, the "new" component would likely have an entirely different preventive maintenance interval.

Situations like this suggest that task packaging for an aircraft be continuously reviewed and updated – a daunting manual task. Customizing a task package for each aircraft, at every return to service following maintenance action can lead to further reductions in out-of-service time and maintenance costs.

C. OPTIMAL TASK PACKAGING

This thesis proposes a decision support model to generate all admissible task groups, and then select from these an optimal task package. Each admissible task grouping must, at the minimum, take into account for each component task the task or "failure mode," failure consequence, task interval, earliest and latest bounds on this interval, and maintenance time required to complete the task.

Some tasks cannot be grouped together, or are *inadmissible*. An illustration of such a mutual exclusion is shown in Figure 8.

Because the current H-60 RCM analysis and review is incomplete, the resulting justified preventive maintenance task listing is not available at this writing. The purpose of this thesis is to explore potential synergism inherent to certain task groupings that can lead to an overall reduction in aircraft out-of-service time. The goal is to develop a

prototypic optimization-based decision support model which demonstrates "proof of concept" using representative preventive maintenance tasks. It is anticipated that this thesis will provide a useful foundation for follow-on work when the RCM analysis and review process is complete.

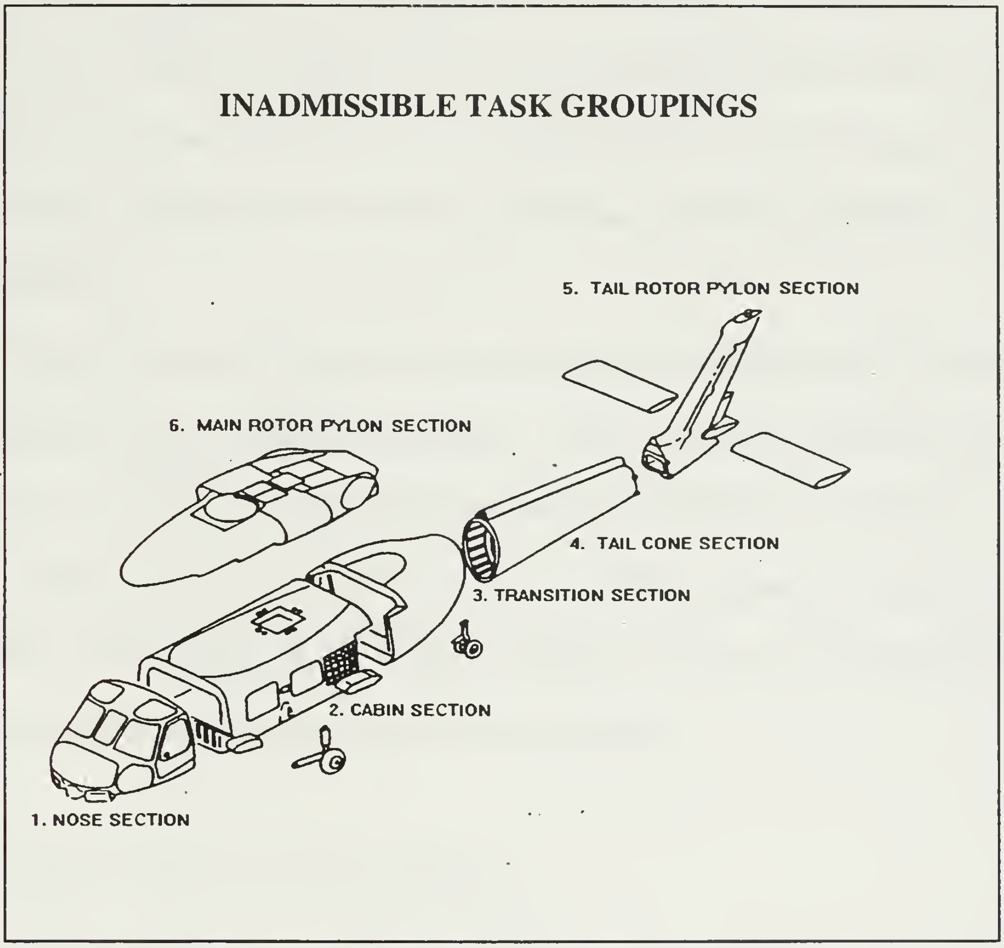


Figure 8. Inadmissible Task Groupings. The H-60 is divided into 6 zones. To identify inadmissible tasks, each zone could be further described by the work content of tasks performed in that zone. For example, a task performed in zone 6 calls for removal of a major main rotor system component. A task in zone 2 requires the aircraft be on jacks. Even though these tasks share a common task interval, either task may preclude concurrent work on the other. These tasks are identified as "mutually exclusive." Other considerations (e.g., the number of available personnel of a required technical skill, or the maximum desired duration of time in maintenance status) may make some tasks mutually exclusive, or inadmissible, for purposes of nominating a task group. (Pollock, 1997b)

IV. AUTOMATED TASK GROUPING AND OPTIMAL TASK PACKAGING

A. TASK INTERVALS AND TASK WINDOWS

For scheduling flexibility, a preventive maintenance task interval has an allowable deviation that is a function of the consequence of failure of the maintained item. For example, a task interval of 20 flight hours, with an allowable deviation of plus or minus 10 per cent, could be performed as early as 18 flight hours or as late as 22 flight hours. A task's "window" is defined as the time from the earliest limit of the allowable deviation to the latest limit.

If a task is performed prior to its earliest scheduled limit, the interval is "re-based" to the time the task is actually performed. In the long run, re-basing preventive maintenance task intervals is costly in terms of performing additional maintenance.

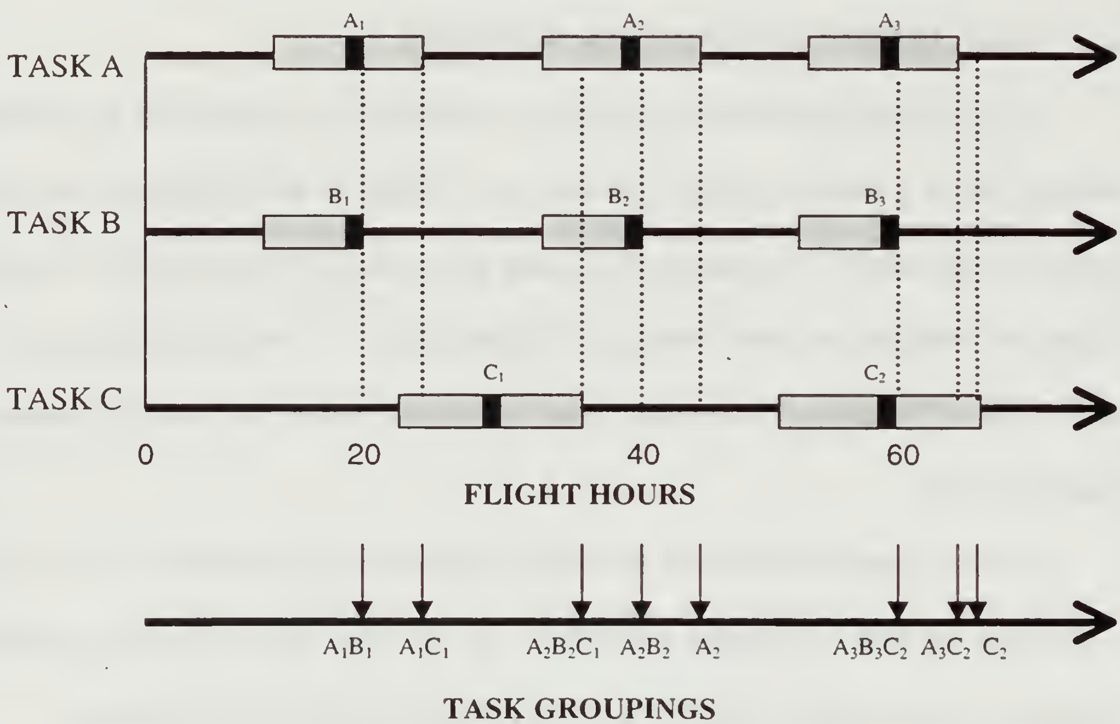
A task that is not performed by the latest limit requires the aircraft to be "grounded", or not authorized for flight. Extending a preventive maintenance task beyond its latest limit is costly in terms of aircraft readiness.

B. GENERATING TASK GROUPINGS

It is clear from the previous discussion that, in order to minimize the total amount of maintenance performed, but while avoiding a penalty of grounding, each task should be performed as late as possible in its window.

A task window expires at the latest limit of the allowable interval deviation. The expiration of a task window identifies a discrete time event.

TASK INTERVALS, WINDOWS AND GROUPINGS



TASK GROUP TIME (HOURS)			
	AB	AC	ABC
INDIVIDUAL	5	7	9
SERIAL	4	6	7
SYNERGISTIC	4	4	5
PARALLEL	3	4	4

TASK WINDOW ▭ TASK INTERVAL ▮

Figure 9. Task Intervals, Windows and Groupings. Suppose tasks A, B and C respectively have recurring 20, 20 and 30 flight hour intervals. Because a different failure consequence is associated with each task, the allowable interval deviation is plus or minus five flight hours for task A, minus five (no plus) flight hours for task B, and plus or minus six flight hours for task C. The task window expirations at the latest limit of the allowable deviation are identified by vertical dotted lines. At the moment a task window expires, all other "open" task windows are identified and "mapped" to a task grouping. In this manner, continuous time is completely and optimally modeled at only eight discrete instants. Multiple instances of each task are distinguished by the task letter and instance subscript (e.g., A_1). Task group times for several task groupings generated in this example are shown for the individual, serial, synergistic and parallel cases. Task performance times are the same as in Figure 6.

At the moment a task window expires, there may be other task windows that are open. The set of all open task windows identifies the feasible tasks that potentially can be performed at that time. This set of feasible tasks becomes a task grouping for that instant in time. In this manner, continuous time is completely and optimally modeled at just this finite number of discrete instants.

The "task group generator", a computer program implemented in Microsoft Excel and Visual Basic for Applications, calculates the task intervals and task windows for every instance of each task, and produces all admissible task groups and task group times.

All information and calculations pertinent to task performance times, task group times, task intervals and task windows reside in this generator. Therefore, to evaluate alternate groupings, additional data would simply need to be introduced into the generator. This makes adjustments to task groupings, because of mutual exclusivity concerns or upcoming deployments, a simple matter.

Fixed time is arbitrarily chosen as a constant that is independent of type or quantity of the candidate maintenance tasks in the group. However, the task group generator can accommodate fixed time modeled by any function of candidate maintenance tasks.

Because actual task performance times were not available at this writing, task performance times for the generator are randomly selected from a Uniform (1,24) distribution. Consequently, variable times developed by the generator are completely arbitrary. As in the case of fixed time, the generator can accommodate any function for task times.

As depicted in Figure 9, the task group generator calculates that the task window for the third instance of task B (identified as B_3) expires at 60 flight hours. The generator also calculates that the task windows for tasks A_3 and C_2 are open at 60 flight hours. The generator records the task grouping $A_3B_3C_2$ as an admissible grouping for that instant and calculates the task group time.

Because it is possible, for instance, to perform any combination of tasks A_3, B_3 and C_2 at, or just after, 60 hours, the problem becomes one of identifying ***the*** task grouping that accomplishes all required maintenance at the lowest cost.

C. OPTIMAL TASK PACKAGING WITH SET PARTITION

Once all preventive maintenance task groupings and task group times are identified, the task packaging problem is formulated as a set partition (e.g., Brown, Dell and Wood, 1997, pp. 25-26; Schrage, 1997, pp. 327-330). A set partition is a special type of linear integer programming model that can be employed in a variety of important military and non-military applications. Figure 10 illustrates a set partition formulation (serial case) for a simple three-task example.

The rows correspond to the task instances, while columns correspond to admissible task groupings. The **costs** are in terms of aircraft out-of-service time: the task group time. A unit coefficient "1" indicates task $\boldsymbol{i}$ is included in task grouping $\boldsymbol{j}$. The constraint "= 1" ensures each task instance is performed.

Note that for every task instance there is a feasible "grouping" of just that task instance. This equates to the statement "one solution is to perform each task by itself." Admitting these "singleton" groupings ensures the packaging problem remains feasible.

A SET PARTITION FORMULATION

		Task Groupings							
		A	B	C	AB	AC	BC	ABC	
	Cost	3	2	4	4	6	5	7	
Tasks	A	1			1	1		1	= 1
	B		1		1		1	1	= 1
	C			1		1	1	1	= 1

Figure 10. A Set Partition Formulation (shown for the serial case). The problem is to select a set of columns (a task packaging of task groups) such that there is exactly one selected element in each row (task), and such that the total cost (out-of-service time) of selected columns is minimal. The task performance times for tasks A, B and C respectively are, again, two, one and three hours. A fixed time of one hour is applied to each task grouping. At a specified aircraft flight hour interval, task B is required to be performed. If task B is performed by itself, a cost of two maintenance hours is incurred (one hour variable time plus one hour fixed time). If tasks A and C must also be performed at approximately the same aircraft flight hour interval as task B, tasks A, B and C can be performed as a group at a cost of seven maintenance hours. Any other packaging of tasks A, B, and C, and all their admissible task groups, results in a higher cost.

In the example presented in Figure 10, the admissible task groupings for task B are B, AB, BC and ABC. If task B is performed by itself, the cost is two hours. If task B is performed with task A, a cost of four hours is incurred. Similarly, the cost is five hours when task B is performed with task C, and seven hours when performed with both A and C.

The mechanism that compares the costs of all feasible packagings of task groups and optimizes for the minimum cost is called the "task packaging optimizer."

In this trivial example, the task packaging optimizer considers the requirement to perform tasks A, B and C, compares the costs of all feasible packagings of task groups and identifies the minimal-cost package as a single task group ABC. However, in selecting a minimal-cost package for a real-world problem, the task packaging optimizer must compare costs among feasible task groups generated for thousands of task instances.

Note that any other packaging of task groups results in a higher cost, or is not feasible. This is equivalent to the statement "since task B must be performed now, and tasks A and C are due soon but can be performed now, it is more efficient to do all three tasks together."

The set partitions in this research were solved by the X-System © (Insight, 1998).

V. RESULTS

A. MODEL INSTANCE

A statistical analysis of the rotor and airframe failure modes indicates that more than one-half of the task intervals in the RCM analysis occur at intervals of less than 1000 flight hours. For this reason, only the 188 failure modes, or tasks, whose task intervals are 1000 flight hours or less are considered as preventive maintenance tasks for input to the task group generator. This flight hour horizon is completely arbitrary, and the generator will accommodate task intervals for any flight hour horizon.

From these 188 preventive maintenance tasks, 376 task instances and 746 admissible task groupings are generated. The set partition problem for the task packaging optimizer consists of 376 rows, 746 columns and 4429 unit coefficients.

Three versions of the model are used to calculate costs and optimal task groupings for each of the cases: serial, synergistic and parallel. In the synergistic case, the numerical results are obtained by arbitrarily designating tasks as either serial or parallel tasks. Task group time is then calculated as fixed time plus the largest variable time of the parallel tasks plus the variable time of the serial tasks. Costs in terms of total hours of maintenance per 1000 flight hours are:

Serial case – 6061 hours;

Synergistic case – 4796 hours; and

Parallel case – 2097 hours.

VI. CONCLUSION AND RECOMMENDATIONS

A. REDUCING TOTAL AIRCRAFT OUT-OF-SERVICE TIME

The task group generator and task packaging optimizer respectively presented in the preceding sections can accommodate completely arbitrary individual task times and task group times. Together, they suggest cohort task groups that constitute an optimal task packaging, as well as the resulting minimal out-of-service time.

Preventive maintenance program developers can hardly be expected to discover provably optimal results such as these manually, let alone quickly. An automated tool is a necessity.

The task group generator subsumes an overwhelming volume of detail and applies simple rules to judge which groups are admissible, and determine how long they would take to accomplish. The task packaging model suggests an optimal set of task groups that performs all the required work in minimal out-of-service time.

Given such automated tools, it becomes possible to customize optimal task packaging for each aircraft, given its most current condition. This would exploit all the available engineering data and advice, while constantly reviewing and minimizing the future out-of-service time for each aircraft.

B. GENERALIZATIONS OF THE MODEL

It may be undesirable to schedule certain task groupings contiguously. For example, suppose the model optimally distinguishes two task groupings that occur within five flight hours of each other. In this situation, the aircraft would be taken out of service twice in short succession to perform scheduled maintenance. An "exclusion constraint"

can be issued by the task group generator to render these two task groups mutually exclusive for optimal task packaging.

Additionally, maintenance managers may want to schedule specific tasks around an aircraft or squadron deployment schedule. The task group generator is flexible enough to accommodate adjustments like this. For example, if a deployment is imminent, the generator can allow task groups of increased complexity and frequency, or even schedule individual tasks prior to their normal earliest window time.

Certain tasks are qualitatively different and should be handled separately by maintenance program developers. One such example is the rod end assembly of the main rotor head assembly, which is removed and replaced every 19,000 flight hours. The frequency of this task is low enough to allow manual scheduling.

C. NECESSARY RESTRICTIVE ASSUMPTIONS

This thesis assumes that an individual task performed any time within its allowable deviation window will not alter the future windows for that task. This conforms with current Navy practice, but does not constitute a limitation of mathematical modeling approaches.

If future task windows are influenced by when the task is actually performed, then it becomes necessary to re-optimize as tasks are completed.

D. IMPLICATIONS FOR THE FUTURE

Driven by cost and readiness issues, many aircraft communities are reengineering maintenance programs toward some type of phased depot maintenance concept.

Accordingly, there is a great deal of interest in models that could be used to optimize an aircraft preventive maintenance program. Currently no model is in use by the Navy.

A preventive maintenance program remains in a dynamic state throughout the life of the maintained weapon system. The aging process generates new failure modes, while keeping weapons systems in the inventory longer exacerbates the degradation of readiness and increases costs. Maintenance program management must be an iterative process that acknowledges changing requirements as a result of aging systems as well as modifications to existing systems. Maintenance program management must continually accommodate actual versus predicted failure rates and new failure modes that occur in aging systems.

Sustaining a well-managed preventive maintenance program requires a continual cycle of RCM analysis, in-service data collection and analysis, and task analysis, which includes task packaging reviews.

Each aircraft, because of its service experience and material condition, presents a unique opportunity for task packaging. This thesis introduces an automated decision support tool that will optimize a preventive maintenance package for the Navy H-60 helicopter. Furthermore, the technique introduced here can be used to customize a task package for each aircraft, at every return to service, following every maintenance action. Such progressive, continuously adaptive maintenance planning can lead to an even greater reduction in Operating and Support costs and improved aircraft readiness.

LIST OF REFERENCES

Air Transport Association of America (ATAA), *Maintenance Program Development Document (MSG-3)*, Rev. 2, September 1993.

Beck, J., Integrated Maintenance Concepts Brief, Naval Air Systems Command, Patuxent River, Maryland, December 1997.

Brown, G.G.; Dell, R.F.; and Wood, R.K., "Optimization and Persistence," *Interfaces*, Vol. 27, No. 5, (September-October), pp. 15-37, 1997.

Commander Naval Air Systems Command (CNASC) Instruction, NAVAIR 4730.10A, Aircraft Service Period Adjustment (ASPA), 15 October 1991.

Commander Naval Air Systems Command (CNASC) Memorandum, "Roadmap to Affordable Readiness," October 1996 (a).

Commander Naval Air Systems Command (CNASC) Memorandum, "A New Direction in Naval Aviation Logistics," 24 December 1996 (b).

Commander Naval Air Systems Command (CNASC), *RCM Analyst Course Guide*, Patuxent River, Maryland, November 1997.

Department of Defense (DoD), Reliability-Centered Maintenance Requirements for Naval Aircraft, Weapons Systems and Support Equipment, MIL-STD-2173(AS), Washington, D.C., 1985.

Gertsbakh, I.B., *Models of Preventive Maintenance*, North-Holland Publishing Company, 1977.

Insight, Incorporated, *"Bausch Extended Format" for Elastic Set Partitioning Problems with Non-Partitioning Rows and Columns*, Manassas, Virginia, March 1998.

Kececioglu, D., *Maintainability, Availability, & Operational Readiness Engineering*, Prentice-Hall, Upper Saddle River, New Jersey, 1995.

Lyons, D., MMHISST Integrated Maintenance Concept Brief, Naval Aviation Depot Cherry Point, North Carolina, June 1997.

Patterson, M. D., *Optimizing the Navy's Transition to Phased Depot Maintenance of H-60 Helicopters*, M.S. Thesis, Naval Postgraduate School, Monterey, California, September, 1997.

Pollock, B., Integrated Maintenance Concept Brief, Naval Aviation Depot Cherry Point, North Carolina, November 1997 (a).

Pollock, B., H-60 IMC Team Leader, Naval Aviation Depot, Cherry Point, North Carolina, Interviews by Author, November 1997 to September 1998 (b).

Schrage, L., *Optimization Modeling With LINDO,* Brooks/Cole Publishing Company, Pacific Grove, California, 1997.

Thomas, V., "The Officer in Charge of Risk," *U.S. Naval Institute Proceedings*, p. 47, August 1997.

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   Naval Postgraduate School
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6. CDR Ronald L. Brown, Code OR/BR 1
   Department of Operations Research
   Naval Postgraduate School
   Monterey, CA 93943-5000

7. Professor David A. Schrady, Code OR/SO 1
   Department of Operations Research
   Naval Postgraduate School
   Monterey, CA 93943-5000

8. Mr. Bruce Pollock 1
   Commanding Officer, NAVAVNDEPOT Cherry Point
   Code 3.2.2 H-60 FST
   PSC Box 8021
   Cherry Point, NC 28533-0021

9. CDR M. H. Albright 1
   5725 Wooden Hawk Lane
   Burke, VA 22015